ECE 345 / ME 380
Introduction to Control Systems
Lecture Notes 1

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Learning Objectives

- Define a control system and describe some applications
- Describe the basic features and configurations of control systems
- Describe control systems analysis and design objectives
- Describe historical developments leading to modern day control theory
- Describe the benefit from studying control systems
- Describe the design process for control systems

References:

- Nise Chapter 1

Outline

- Practical information
  - Course logistics
  - Textbook
  - Relevance to your degree goals
- What is control?
- History of control theory
- Examples
  - Robotic vehicles
  - Aircraft avionics
  - Social and environmental systems
- Controller design process

Practical information: Resources

Textbook

- *Control Systems Engineering*, N. Nise, 8^{th} edition, 2019. Wiley. Additional online resources at `http://www.wiley.com/college/nise/`.

People

- Professor: Dr. Meeko Oishi, ECE 134C, `oishi@unm.edu`
- TA: Mr. Connor Halsey, `chalsey@unm.edu`

Note: Many images used in these lecture notes are from the Nise textbook.

Which *four* of the following items are the most important characteristics in recent college graduates for hiring companies?

Nat'l Assoc. of Colleges and Employers

- **Critical Thinking/Problem Solving:** Exercise sound reasoning to analyze issues, make decisions, and overcome problems. The individual is able to obtain, interpret, and use knowledge, facts, and data in this process, and may demonstrate originality and inventiveness.
- **Oral/Written Communications:** Articulate thoughts and ideas clearly and effectively in written and oral forms to persons inside and outside of the organization. The individual has public speaking skills; is able to express ideas to others; and can write/edit memos, letters, and complex technical reports clearly and effectively.
- **Teamwork/Collaboration:** Build collaborative relationships with colleagues and customers representing diverse cultures, races, ages, genders, religions, lifestyles, and viewpoints. The individual is able to work within a team structure, and can negotiate and manage conflict.
- **Digital Technology:** Leverage existing digital technologies ethically and efficiently to solve problems, complete tasks, and accomplish goals. The individual demonstrates effective adaptability to new and emerging technologies.
- **Leadership:** Leverage the strengths of others to achieve common goals, and use interpersonal skills to coach and develop others. The individual is able to assess and manage his/her emotions and those of others; use empathetic skills to guide and motivate; and organize, prioritize, and delegate work.
- **Professionalism/Work Ethic:** Demonstrate personal accountability and effective work habits, e.g., punctuality, working productively with others, and time workload management, and understand the impact of non-verbal communication on professional work image. The individual demonstrates integrity and ethical behavior, acts responsibly with the interests of the larger community in mind, and is able to learn from his/her mistakes.
- **Career Management:** Identify and articulate one's skills, strengths, knowledge, and experiences relevant to the position desired and career goals, and identify areas necessary for professional growth. The individual is able to navigate and explore job options, understands and can take the steps necessary to pursue opportunities, and understands how to self-advocate for opportunities in the workplace.
- **Global/Intercultural Fluency:** Value, respect, and learn from diverse cultures, races, ages, genders, sexual orientations, and religions. The individual demonstrates, openness, inclusiveness, sensitivity, and the ability to interact respectfully with all people and understand individuals' differences.

Practical information: Relevance to your degree

Clicker question

Consider what you want to get out of your college education. Which of the following goals is *most* important to you?

A. Acquiring factual knowledge
B. Learning how to use factual knowledge in new situations
C. Developing skills to continue learning after college

Practical information: Relevance to your degree

Clicker question

Which of these three goals would be best to make headway on outside of class on your own, by reading and studying?

A. Acquiring factual knowledge
B. Learning how to use factual knowledge in new situations
C. Developing skills to continue learning after college

Which of these three goals would be best achieved in class?

Practical information: Relevance to your degree

This course is structured to help students with all three highly worthy goals.

However, making progress on all three goals will require students to do work ahead of some class sessions, so that class time can be spent on higher-level goals.

Students learn best when they:

- Take an active role
- Discuss what they are reading
- Practice what they are learning
- Apply practices and ideas

Practical information: Relevance to your degree

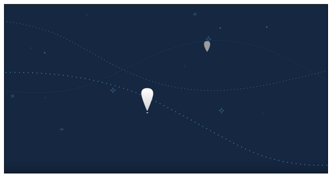
Students will get the most out of the course when they:

- Complete assigned pre-class work before class
- Fully participate in in-class activities (individual as well as group work)
- Apply factual knowledge to problems
- Monitor their learning
- Ask questions and follow up on areas of confusion

What is control?

Control system

- An interconnection of components that provide a desired system response
- Key enabling technology in all branches of engineering
- Used whenever some quantity (e.g., temperature, altitude, speed, concentration) must be made to behave in some desirable way over time
- Often exploits *feedback* to help regulate the system response



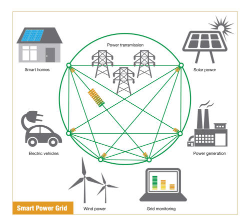
a) https://youtu.be/MiEZfRh-h-s (Google)

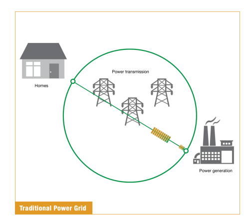
(b) Urban Air Mobility (NASA)

What is control?

Control system

- Compare actual behavior with desired behavior
- Take corrective action based on the difference
- Deceivingly simple idea, but very powerful concept



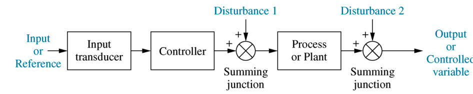


https://www.news.gatech.edu/features/building-power-grid-future

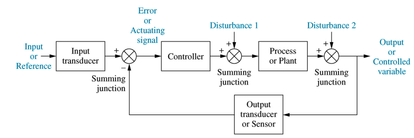
What is control?

Open-loop vs. Closed-loop

- Open-loop



- Closed-loop



What is control?

Open-loop vs. Closed-loop

OL	CL	Description
		Cannot compensate for disturbances that affect the plant
		Higher accuracy and robustness to disturbances
✓		Commanded by the input
	✓	Commanded by the error via feedback
		Relatively more complex and expensive
		Improved performance and stability

(Curiosity Rover)

Examples: Mobile robotics

Applications
- Search and rescue
- De-mining
- Remote operation

(CDC 2019)

Challenges
- Autonomous navigation in uncertain environments
- Limitations of sensing and actuation
- Safe human-robot interaction

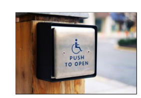
(ACC 2018)

What is control?

Clicker question

Consider the following four devices:





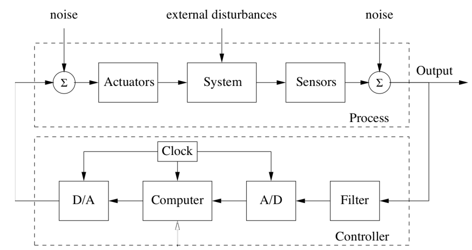
Which option most correctly describes those devices that are *closed-loop* systems?

A. Conventional toaster
B. Thermostat
C. ABS
D. Push-button door opener
E. Thermostat, ABS, & Door opener

What is control?

Computer-controlled feedback system

- Sensing, computation, and actuation



What is control?

Elements of a control system

- The **plant** or **process** is the physical system.
- **Actuators** are used to apply forces or torques to the physical system.
- **Sensors** are used to measure system behavior.

A *dynamical* system is one whose behavior changes over time.

Consider the problem of cruise control:

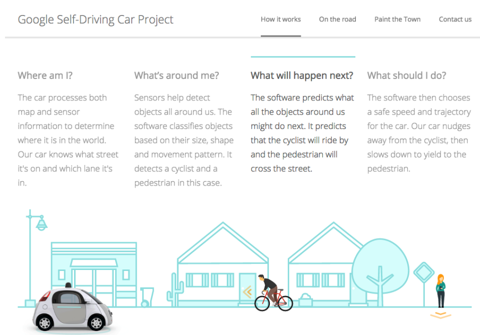
- The plant is the automobile
- The actuator is the engine which generates propulsive forces that turn the wheels
- The sensor is the tachometer which measures the vehicle's speed

What are the plant, actuator, and sensor for an elevator? A thermostat?

What is control?

Elements of a control system

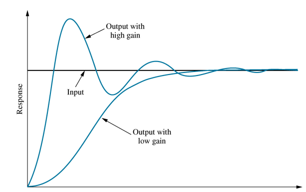
- Desirable sensor attributes
  - Reliability
  - Accuracy
  - Noise immunity
  - Non-intrusiveness
  - Linearity
- Desirable actuator attributes
  - Linearity
  - No backlash, stiction, hysteresis
  - Appropriate size for the system
- Implementation and control often via embedded microprocessors and electromechanical actuators

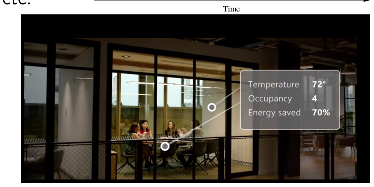


What is control?

Common goals

- Stability
- Performance
  - Transient response (short-term characteristics)
  - Steady-state response (long-term characteristics)
- Robustness to disturbances, modeling errors, noise, etc.
- Optimality
- Adaptability
- Ability to "learn"

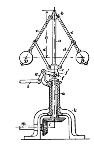
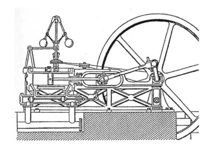




https://www.youtube.com/watch?v=TI7pQ5zSEJs

History of Control

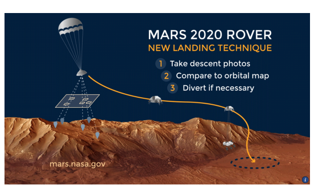
- Float regulators in water clocks, 300 BC
- Windmill speed control, 1745
- Watts' flyball governor, 1769
- Lyapunov's stability criteria, 1892
- "Classical" control, 1940s
- "Modern" control, 1970s
- Robust, nonlinear, optimal, H_∞, discrete, hybrid, embedded, cyber-physical...

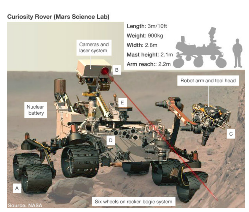



Examples: Mars 2020

Reliable autonomy for spacecraft

- Feedback-based entry, descent, and landing





http://mars.nasa.gov/mars2020/mission/timeline/entry-descent-landing/

Examples: Navigation on an Asteroid

Robust space robotics

(JPL Hedgehog)

http://www.jpl.nasa.gov/video/details.php?id=1398

Examples: Aircraft Flight Management System

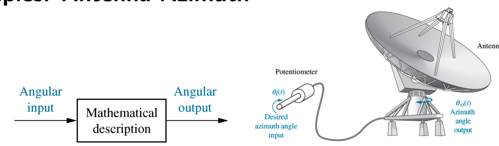
Avionics systems

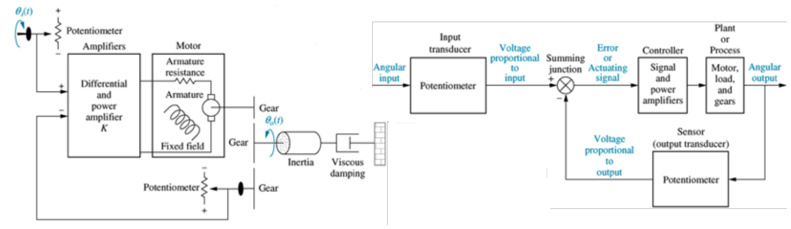
www.nasa.gov/centers/armstrong/features/auto-gcas_performs_fourth_confirmed_save.html

Examples: Antenna Azimuth

Fine position control

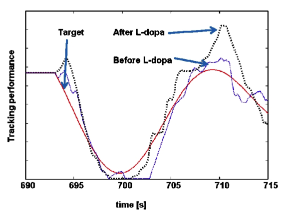
- Desired azimuth angle is input
- Actual azimuth angle is output

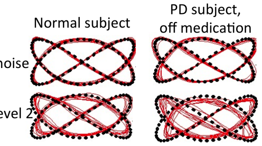


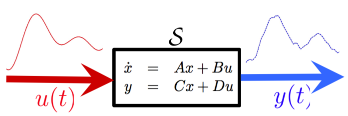


Examples: Parkinson's Disease

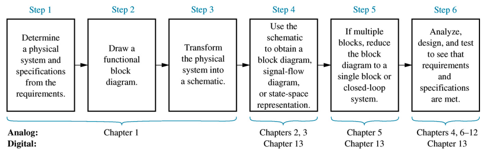
Input-output models of manual pursuit tracking







Controller Design Process



This class will focus analysis and design via classical control techniques.

1. Develop mathematical models
2. Quantify "good" behavior
3. Establish whether or not the system will meet requirements for good behavior
4. Controller design to *change* the behavior of the system

Controller Design Process

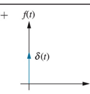
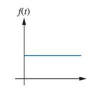
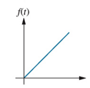
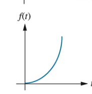
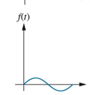
Test signals

- Facilitate analysis and design of control systems
- Set of common characteristics that describe system response
- Can infer system response to other signals
- Used to quantify "good" behavior

These signals will appear throughout the course.

Recommendation: Become familiar with these signals and develop an intuition for what they represent in physical systems!

TABLE 1.1 Test waveforms used in control systems

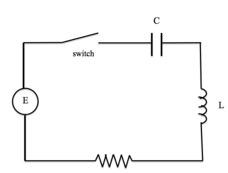
Input	Function	Description	Sketch	Use
Impulse	$\delta(t)$	$\delta(t) = \infty$ for $0- < t < 0+$ $= 0$ elsewhere $\int_{0-}^{0+} \delta(t)dt = 1$		Transient response Modeling
Step	$u(t)$	$u(t) = 1$ for $t > 0$ $= 0$ for $t < 0$		Transient response Steady-state error
Ramp	$tu(t)$	$tu(t) = t$ for $t \geq 0$ $= 0$ elsewhere		Steady-state error
Parabola	$\frac{1}{2}t^2u(t)$	$\frac{1}{2}t^2u(t) = \frac{1}{2}t^2$ for $t \geq 0$ $= 0$ elsewhere		Steady-state error
Sinusoid	$\sin \omega t$			Transient response Modeling Steady-state error

Controller Design Process

Clicker question

Consider a circuit with a DC voltage source that is controlled by a switch. When the switch is closed, voltage is applied to the circuit. Which of the following most closely describes the applied voltage signal as a function of time?

1. An impulse signal
2. A step signal
3. A parabolic signal
4. A sinusoidal signal



Controller Design Process

1. Identify
   (a) What you want to control (the *process* or *plant*)
   (b) How you can control it (via *actuators*)
   (c) How you can measure it (via *sensors*)
2. Formulate a mathematical model, in either
   (a) The time domain (via *state-space models* and *differential equations*)
   (b) The frequency domain (via *transfer functions*)
3. Linearize around a desired operating point, if necessary
4. Design a controller for the linear system
5. Optimize its parameters to meet desired control objectives

Controller Design Process

Model development

- Higher order models can only be justified where there is little uncertainty
- Control-relevant models are often quite simple compared to the true physical system, and generally combine physical reasoning with experimental data
- Actuators should be included as they are often nonlinear and have their own dynamic behavior
- Linear models are most often used in analysis and design

Controller Design Process

Given a physical system,

1. Look up relevant physical laws
2. Define inputs and outputs
3. Formulate the mathematical model; list any assumptions
4. Derive equations of motion
5. Establish initial conditions
6. Solve and verify existence of solutions
7. If necessary, re-analyze or re-design the system

This works well for many mechanical and electrical systems.

Controller Design Process

For mechanical systems:

- Newton's second law of motion

$$\sum F = ma$$
$$\sum \tau = I\alpha$$

For electrical systems:

- Kirchhoff's current law (KCL): At every node, the sum of the currents entering the node equals the sum of the currents leaving the node.
- Kirchhoff's voltage law (KVL): Around any full loop in a circuit, the sum of the potential differences across all elements traversed by the loop is zero.

Key Concepts

- Open-loop vs. closed-loop control
- Sensing, computation, and actuation
- Test signals